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# The Mode of Combined Multi-speed Freight Trains under Separation of Passenger and Freight Transport

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**Abstract**

It is analyzed in this paper the type and the operation mode of freight trains, and the concept of freight trains-groups is introduced. The composition of void time of train diagram is discussed as well. Based on these analyses, an optimization model was established to study the combination mode of multi-speed freight trains with two objectives: the maximum benefit of freight transport and the minimum void time of train diagram. Finally, the results of an example indicate that the presented model proves to be applicable to address real-world issues.



*Keywords*: operation mode; freight trains-group; void time of train diagram; optimized model

## 1. Introduction

With the gradual construction of Passenger Dedicated Lines (PDLs) according to the plan of "four verticals and four horizontals", it is an inevitable trend that passenger transport and freight transport will separate on main railway corridors. Under this situation, carrying capacity will be relative enough, which provides ripe conditions for freight trains with different speeds running on the same railway section. Low speed freight trains play a dominant role under the mode of freight transport and passenger transport mixed running, differing from that, the proportion of low speed, middle speed and high speed freight trains on the same railway section are determined by each transport demand under the separation of

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passenger and freight transport. But the carrying capacity will be reduced by the overtaken among high speed trains, middle speed trains and lower speed trains, so their proportion and organization scheme are essential for the benefit and quality of freight trains in the section.

In previous studies (Meng 2010, Sun 2010), scholars paid more attention to the combination mode of multi-speed passenger trains on PDLs and the combination mode of different kinds of trains on line for mixed freight and passenger transport. Three combination modes on passenger dedicated line and the concept of “overtaking trains-group” were defined (Xu 2003). Hu studied different combination modes on line for mixed freight and passenger transport, and made an adaptation analysis on carrying capacity about the mode of “running in group”, considering distances between adjacent stations and so on(Hu 2005). But as to the mode of combined multi-speed freight trains under the separation of passenger and freight transport, researches are less. So based on existing studies, the problem will be analyzed with the consideration of the dynamic characteristic of freight demand.

## 2. Problem statement

### *2.1. The type of freight trains under the separation of passenger and freight transport*

The separation of passenger transport and freight transport releases carrying capacity of a railway line dissipated by mixed transport. Under this situation, domestic scholars did a lot of research and defined the type of freight trains including general freight train, through freight train, rapid freight train, container freight train and special freight train (He 2010). According to the characteristics of these freight trains, we define their attribute and manifestation, where the attribute indices include velocity property, demand-level coefficient and benefit coefficient. In detail, velocity property is set as low-speed (80km/h), middle-speed (120km/h) and high-speed (160km/h); demand-level coefficient is a dynamic value and is related to the ratio of freight demand and real carrying capacity of the line; benefit coefficient is a dynamic value too and is related to the ratio of per unit earning and the capacity of train working diagram occupied.

### *2.2. Operation modes of freight trains under the separation of passenger transport and freight transport*

Under the separation of passenger transport and freight transport, the operation of freight trains can be summarized into two modes: all kinds of freight trains mixed running all day around or running in a group.

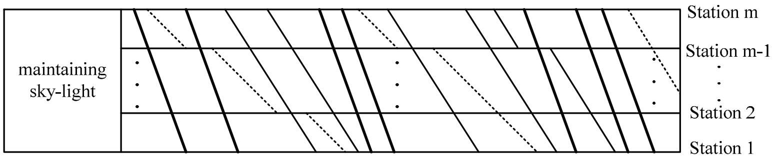


Fig. 1. The mode of all kinds of freight trains mixed running all day around

From Fig. 1 we can see the schematic diagram of the operation mode that all kinds of freight trains mixed run all day around (taking down direction trains for example), where the trains randomly combine randomly. But under the separation of passenger transport and freight transport, the increasing of the kind of freight trains and their speed difference will inevitably lead to the overtaking among them, so this mode generates more capacity loss. In general, as to the line section where multi-speed trains are mixed running on, larger speed difference results in a higher deduction coefficient of high speed trains and smaller carrying capacity of that line section. Of course, when all kinds of freight trains mixed run all day around, their equilibrium is better, and the fluctuation of overtaking at each station is smaller, so the number of tracks needed in every station is even. On the other hand, this operation mode does not affect the station work (e.g., Arrival & departure of trains) badly, especially for marshalling stations. Considering the influence on the capacity of lines and fixed equipments, this operation mode is suitable for the lines with smaller traffic density and enough capacity.

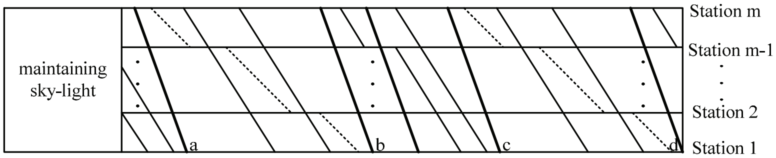


Fig. 2. The mode of all kinds of freight trains running in a group

Fig. 2 shows the schematic diagram of the operation mode that all kinds of freight trains run in group (taking down direction trains for example), where the train diagram is described by regular patterns, for example the train-group structure in the period $a-b$ and $c-d$ are the same. The train-group, a new concept introduced in this paper, denotes the multi-trains with the same or similar properties and fixed structure dispatching continuously. It exhibits same or similar structure and can be described for many times on train diagrams (Hu 2005). The definition is as follows: a certain kind of train in the train-group is called a train element, and correspondingly, the number of the kinds of trains in the train-group is called the element number and the kind with the most trains is called the principle element.

## *2.3. Void time of train diagram*

In this paper, we define another concept called "void time of train diagram". In Fig. 3, void time of train diagram is made up of two parts. On one hand, there exit overtakings between trains of different speeds in the train-group, which will lead to some capacity loss. On the timeline, it manifests as void time. On the other hand, the time needed between adjacent train-groups is void time too.

There are two kinds of overtaking patterns in freight train-groups.

(1) Combination of two kinds of speed freight trains

Based on a great deal of investigation of auto-block double line sections, the Academy of Railway Sciences deduced empirical formulas for calculating the reduction coefficient of freight trains with higher speed, where the trains were in disperse scheduling ($\varepsilon'$) and tracing scheduling ($\varepsilon''$) respectively ( Hu 2004).

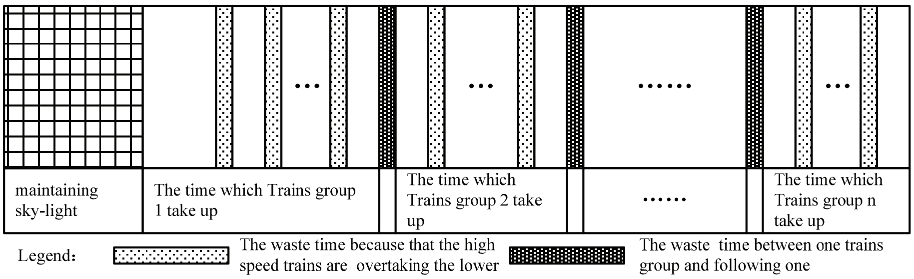


Fig. 3. The structure of multi-speed freight trains mixed running

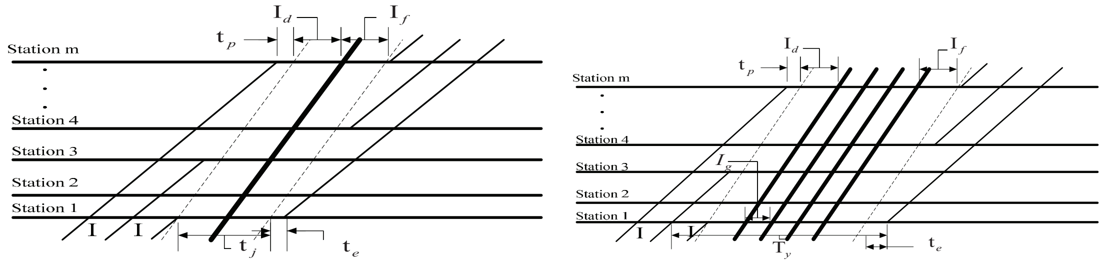


Fig. 4. Composition of the reduction coefficient of the two kinds of speed freight trains: (a) Disperse scheduling, (b) Tracing scheduling

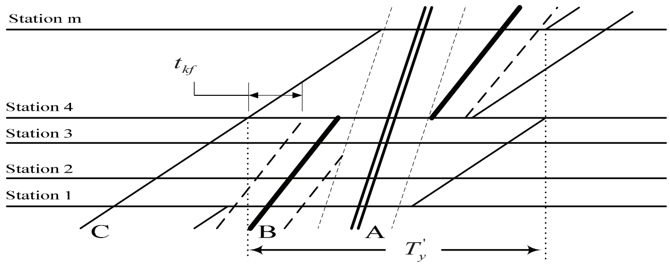


Fig. 5. A-th kind of freight trains overtaking B-th and C-th kind of freight trains

$$\varepsilon^{'} \approx 2\Delta + 0.05 - 0.0375t_c + \left(1.025t_c + 3.6\right)/I \tag{1}$$

$$\varepsilon^{''} \approx \left(1.07 - 0.0053n_g + 10^{-5}n_g^2\right) \cdot \varepsilon^{'} \tag{2}$$

where $\Delta$ is the ratio of the running time of higher speed trains and that of lower speed trains; $I$ is the trace interval of lower speed trains, min; $t_c$ is the speed gap between different kinds of trains at each station; $n_g$ is the number of tracing freight trains with higher speed.

(2) Combination of three kinds of speed freight trains

There exists in the line, where multi-speed trains running on, the phenomenon that middle-speed freight trains (B-th kind) are overtaken by high-speed freight trains (A-th kind), and this type is called complex overtaking train-group, as is shown in Fig. 5 (Hu 2005).

The reduction coefficient of complex overtaking train-group can be calculated with the following formula:

$$\varepsilon^{'''} = (I_d + 2I_f + \Delta t_{gi} + t_{qt} + \delta t_i)/I \tag{3}$$

where $\Delta t_{gi}$ is the running time gap between rapid-speed freight trains and rapid-speed freight trains in the section after the $i$ -th station; $\delta t_i$ is the additional time of middle-speed trains on the $i$ -th station.

So the total void time in freight trains-group ( $T_{kf}^{'}$ ) satisfies the formula (4).

$$T_{kf}^{'} = \sum_{i \in I}\sum_{j \in J} t_{ij} \qquad (i = 1, 2, \cdots, n; j = 1, 2, \cdots, m) \tag{4}$$

$$t_{ij} = I\left(\varepsilon_{ij} - 1\right) \qquad (i = 1, 2, \cdots, n; j = 1, 2, \cdots, m) \tag{5}$$

where $t_{ij}$ is the void time of the $i$ -th freight trains-group at $j$ -th overtaking; $\varepsilon_{ij}$ is the reduction coefficient of the $i$ -th freight trains-group at $j$ -th overtaking.

In the adjacent trains-groups, the void-time is determined by the speed pattern of the last train in the former trains-group and that of the first train in the latter one. In this paper, we set three kinds of train speeds, which are A, B and C and correspondingly there are $C_3^1 \cdot C_3^1 = 9$ kinds of match-types combined by adjacent trains-groups. If the anterior train is with a higher speed than the posterior one, there is no limit on the minimum interval time between adjacent trains-groups.

## 3. Optimization model

According to the above discussion, we establish an improved model to study the combination mode of multi-speed freight trains with the consideration of two optimization objectives: the maximum benefit of freight transport and the minimum void time of train diagram. The former objective is intuitive, because the railway transportation enterprise should pursuit maximum benefit on the basis of serving the whole. And the void time of train diagram embodies the utilization ratio of capacity. Under certain technical conditions, a lower void time of train diagram leads to a larger flexibility of the capacity, which is helpful to optimizing the freight transportation organization.

### *3.1. Definition of parameters and decision variables*

The parameters are defined as follows: $E$ is the set of freight trains-groups; Z is the set of reduction coefficients; $TR$ is the set of speed-type of freight trains, where $TR = \{A = 80, B = 120, C = 160\}$ ; $S$ is the set of the kind of freight trains; $O$ is another set of speed-type of freight trains, where the elements less than 2 and $O \in TR$ ; $W$ represents the transportation benefit of section; $T_{kf}$ is the total void time of train diagram; $FR_i$ and $LR_i$ stand for the speed-type of the first and last freight train in the $i$ -th trains-group respectively, $FR_i \in TR$ and $LR_i \in TR$ ; $y_e$ is the times selected of the $e$ -th freight trains-groups, $e \in E$ ; $t_{\min}$ is defined as the minimum interval between adjacent freight trains-groups; $n$ is the section capacity of paralleled train diagram; $\varepsilon_s^o$ , $xn_s^o$ , $sn_s^o$ and $x_i^{s,o}$ respectively mean reduction coefficient, demand, providing capacity and per unit earning of the $s$ -th kind of freight train at $o$ -th speed-type. $\sigma_s^o$ （ $s = p, z, k, j, t$ ; $o = d, z, g$ ） represents the satisfied degree of the $s$ th kind of train with the $o$ th velocity level, $\eta_s^o$ is the benefit of the $s$ th kind of train with the $o$ th velocity level.

We define two decision variables: $x_i^{s,o}$ is the number of the $s$ -th kind of freight train at $o$ -th speed-type in the $i$ -th trains-group; $y_i^e$ is the $i$ -th freight trains-group belonging to $e$ -th kind on train diagram according to time series.

### *3.2. Two membership functions*

As above mentioned, $\left(q_1^e, q_2^e, \cdots, q_i^e\right) e \in E$ is a combination mode of the freight trains-groups. Formula (6) is the membership function to calculate the reduction coefficient of the freight trains-groups, and formula (7) is used to judge with or without the limit of minimum interval time between adjacent trains-groups.

$$f\left(x_i^{s,o}, y_i^e\right) = \begin{cases} \varepsilon' & o \le 2 \ \ and \ \ e \le 4 \\ \varepsilon'' & o \le 2 \ \ and \ \ 4 < e \le 10 \\ \varepsilon''' & o = 3 \end{cases} \tag{6}$$

$$g\left(LR_i, FR_{i+1}\right) = \begin{cases} 1 & LR_i = FR_{i+1} \\ 0 & LR_i \ne FR_{i+1} \end{cases} \tag{7}$$

### *3.3. Objective functions and constraints*

Based on the above analysis and the definition of variables, we set two objective functions.

For the sake that three attributes of different kinds of trains are not identical and that various transportation demands are unbalanced, benefit coefficient $\eta_s^o$ and demand-level coefficient $\sigma_s^o$ are introduced in the objective function of the maximum benefit of freight transport.

$$\max\ W = \sum_{s\in S}\sum_{o\in O}\sum_{i\in I}\left(\eta_s^o c_s^o\right)\cdot\left(\delta_s^o x_i^{s,o}\right) \tag{8}$$

The void time of trains-groups and the minimum interval time between adjacent trains-groups are key factors in the objective function of the minimum void time of the train diagram shown in the formula (10). The total void time of the trains-group is related to the trains' reduction coefficients in it; the minimum interval time between adjacent trains-groups are related to $LR_i$ ,$FR_{i+1}$ .

$$\min\ T_{kf} = \sum_{s\in S}\sum_{o\in O}\sum_{i\in I}\left(f\left(x_i^{s,o}, y_e\right)-1\right)I + \sum_{1}^{i-1} g\left(LR_i\ ,FR_{i+1}\right)\cdot t_{\min} \tag{9}$$

Constraints:

(1) Upper bound constraint of decision variables

$$\sum_{i\in I} x_i^{s,o} \le xn_s^o \tag{10}$$

(2) Constraint of capacity

$$\sum_{s\in S}\sum_{o\in O}\varepsilon_s^o x_s^o \le n \tag{11}$$

(3) Constraint of benefit coefficient

$$\eta_s^o = \frac{c_s^o}{\varepsilon_s^o \cdot I} \tag{12}$$

(4) Constraint of demand-level coefficient

$$\sigma_s^o = \begin{cases} \dfrac{sn_s^o}{xn_s^o} & sn_s^o < xn_s^o \\ 1 & sn_s^o \ge xn_s^o \end{cases} \tag{13}$$

(5) Constraint of decision variables

$$x_s^o \ge 0 \text{ and is an integer} \tag{14}$$

As for multi-objective programming, there is not a general algorithm. We adopt the hybrid genetic algorithm (Huang 1999) to solve the presented model.

## 4. Numerical example

We study the combination mode of various kinds of freight trains in a railway section under the separation of passenger transport and freight transport using the presented model and algorithm.

### *4.1. The value of parameters*

(1) The demand of different kinds of freight trains

In order to verify applicability of the model, 7 groups of transportation demand are selected as are shown in Table.1. In 1-3 groups, some certain kind of train is in the majority; in 4-6 groups, some certain kind of train is in the minority; in group 7, three kinds of trains are even. In table 1, the PH, ZD, KH, JH, TH represents general freight train, through freight train, rapid freight train, container freight train and special freight train respectively, and A, B, C is train's speed level, 160 km/h,  120 km/h and 80 km/h respectively. When the A, B, C is used as subscript, such as $\mathrm{PH_C}$, it means that the speed level of general freight train is C.

Table 1. The demand of different kinds of freight trains (train/day)

| Train type | $PH_C$ | $ZD_C$ | $ZD_B$ | $KH_B$ | $KH_A$ | $JH_C$ | $JH_B$ | $TH_C$ | Total | C: B: A |
|---|---|---|---|---|---|---|---|---|---|---|
| Group 1 | 45 | 10 | 5 | 10 | 10 | 10 | 5 | 5 | 100 | 7:2:1 |
| Group 2 | 5 | 8 | 40 | 20 | 10 | 5 | 10 | 2 | 100 | 2:7:1 |
| Group 3 | 5 | 3 | 10 | 5 | 70 | 1 | 5 | 1 | 100 | 1:2:7 |
| Group 4 | 20 | 10 | 20 | 10 | 10 | 10 | 15 | 5 | 100 | 4.5:4.5:1 |
| Group 5 | 20 | 10 | 2 | 3 | 45 | 10 | 5 | 5 | 100 | 4.5: 1: 4.5 |
| Group 6 | 5 | 3 | 20 | 15 | 45 | 1 | 10 | 1 | 100 | 1:4.5:4.5 |
| Group 7 | 10 | 10 | 15 | 15 | 33 | 10 | 3 | 4 | 100 | 1:1:1 |

Table 2. The per unit earning of each type of freight trains

| Train type | $PH_C$ | $ZD_C$ | $ZD_B$ | $KH_B$ | $KH_A$ | $JH_C$ | $JH_B$ | $TH_C$ |
|---|---|---|---|---|---|---|---|---|
| Profit | 100 | 120 | 140 | 160 | 200 | 130 | 150 | 110 |

Table 3. The optimization result of $y_i^e$

| Trains-groups | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Group 1 | 4 | 7 | 2 | 1 | 1 | 3 | 4 | 2 | 7 | 1 | 2 | 10 | 4 | 7 | 2 | 2 | 7 | 4 | 1 | / | / |
| Group 2 | 4 | 2 | 8 | 1 | 6 | 9 | 2 | 1 | 8 | 1 | 9 | 4 | 4 | 1 | 8 | 2 | 1 | 6 | 2 | 4 | / |
| Group 3 | 5 | 7 | 1 | 3 | 3 | 2 | 7 | 5 | 5 | 3 | 1 | 2 | 2 | 7 | 5 | 4 | 1 | 3 | 2 | 1 | / |
| Group 4 | 3 | 4 | 2 | 8 | 9 | 1 | 2 | 3 | 4 | 8 | 9 | 10 | 9 | 1 | 3 | 4 | 2 | 8 | 9 | 1 | 1 |
| Group 5 | 7 | 6 | 4 | 3 | 1 | 2 | 4 | 3 | 7 | 1 | 4 | 2 | 7 | 7 | 6 | 3 | 4 | 1 | 2 | / | / |
| Group 6 | 2 | 9 | 4 | 4 | 1 | 8 | 4 | 2 | 8 | 6 | 9 | 2 | 1 | 1 | 8 | 4 | 6 | 2 | 6 | 2 | / |
| Group 7 | 8 | 8 | 9 | 1 | 3 | 4 | 8 | 9 | 1 | 3 | 4 | 2 | 8 | 10 | 2 | 1 | 8 | / | / | / | / |

(2) Parameters of a section

The section capacity (up direction) of the paralleled train diagram is set to 132 (train/day); the tracing interval is 10 min; the minimum interval time between trains-groups are 15 min; per unit earning of each type of freight trains is shown in Table 2, which is obtained by an expert evaluation method taking the per unit earning of PH train for reference.

(3) Restricted parameters of tracing running and the type of trains-group

In theory, tracing running of the same kind of trains is helpful in improving the capacity of the paralleled train diagram, but it will lead to unbalance transportation and have bad influences on the operation of adjacent technical station. With previous study (Meng 2010), we in this paper set the maximum number of tracing trains as 3, and based on it, we use the 10 modes of trains-group in reference (Hu 2005).

### *4.2. Calculation result*

We obtain the optimum results in Table 3 and Table 4, where Table 3 records the optimized value of $y_i^e$ under 7 groups' transportation demand. From Table 4, we can see the optimized value of $\sigma_s^o$ and the transportation benefit and void time under various transportation demands.

Table 4. The optimization result of $\sigma_s^o$

| Train type | PHC | ZDC | ZDB | KHB | KHA | JHC | JHB | THC | Trains number | Transport benefits | Void time(min) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Group 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 100 | 12600 | 155 |
| Group 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 100 | 14630 | 152 |
| Group 3 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 100 | 18050 | 137 |
| Group 4 | 0.89 | 0.91 | 1 | 1 | 1 | 1 | 1 | 0.93 | 95 | 13170 | 320+63 |
| Group 5 | 0.93 | 1 | 1 | 1 | 1 | 1 | 0.89 | 1 | 96 | 15210 | 320+51 |
| Group 6 | 0.87 | 1 | 0.93 | 1 | 1 | 1 | 0.91 | 1 | 96 | 16270 | 320+53 |
| Group 7 | 0.74 | 0.91 | 1 | 1 | 1 | 0.89 | 0.91 | 0.81 | 92 | 14500 | 320+96 |

## 5. Conclusions

To verify the presented model, we calculated the capacity according to the 7-th group transportation demand in Table 1 using a graphical method. We obtained the trains running stochastic sequence, and draw the train working diagram. It was found that that the capacity under equal conditions is 83 (train/day), which is smaller than 92 (train/day) obtained from the presented model. Meanwhile, we were able to obtain the void time of a train diagram to be 510 min/day under the mixed freight trains. . When mixed freight trains were running in groups, the void time is 284 min/day on average.

From the results, it is concluded that the void time of train diagram can be decreased by optimizing and combining the sequence of trains-groups under different transportation demands. Meanwhile, the proposed model could bring benefits to the current transportation system and improve its quality.

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